Relating Potato Yield and Quality to Field Scale Variability in Soil Characteristics

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ABSTRACT

Causes of within-field spatial variability in potato (*Solanum tuberosum* L.) yield are not well understood. To address this, a study was conducted from 1998 to 2000 on a commercial farm in southeastern Washington. Soil samples were collected from four center-pivot-irrigated, uniformly fertilized fields on a 0.4-ha grid interval prior to potato planting and analyzed for nitrate-N, ammonium-N, P, K, organic matter, pH, and texture. The elevation of each grid point was also recorded. Four to five days before commercial harvest, potatoes were collected from a 3-m row length at each original grid point using a one-row digger. The potatoes were weighed, sorted into five weight classes, and evaluated for specific gravity. Correlation and stepwise regression analyses were conducted to test relationships between soil-based and yield variables. Factors driving yield varied between fields. Soil texture components (sand, silt, clay) had stronger impact on yield than with the soil chemical properties we measured. However, all four fields showed an inverse relationship between specific gravity and soil test K, although the correlation coefficients and contributions to regression models were relatively low. Finding a general prescription formula for goals other than higher yield (e.g., nutrient-leaching potential) may be feasible. The consistent relationship of soil textural components in our models suggest that monitoring available soil water, a factor closely related to soil texture, should be included in any future work.

RESUMEN

Las causas de la variabilidad espacial del rendimiento de la papa dentro de un mismo campo no son bien entendidas. Con el fin de comprenderlas, entre 1998 y 2000 se realizó un estudio en una parcela comercial del sudeste de Washington. Antes de la siembra del tubérculo se recolectaron muestras de suelo de 4 centros pivote del mismo campo irrigadas y fertilizadas uniformemente en cuadrículas intercaladas de 0.4 h y se sometieron a análisis de nitrato-N, amonio-N, P, K, materia orgánica, pH y textura. También se registró la elevación de cada punto de la cuadrícula. Cuatro a cinco días antes de la cosecha comercial, se recogieron papas de una hilera de 3m de longitud de cada punto original de la cuadrícula usando una cosechadora de un surco. Las papas fueron pesadas, clasificadas en cinco categorías de acuerdo a su peso y evaluadas en su gravedad específica. Se realizaron análisis de correlación y regresión escalonada para probar la relación entre el lecho del suelo y las variables de rendimiento. Los factores que impulsan al rendimiento varían entre campos. Los componentes de la textura del suelo (arena, sedimentos, arcilla) tuvieron un impacto más fuerte sobre los rendimientos que las características químicas del suelo que medimos. Sin embargo, los cuatro campos mostraron una relación inversa entre la gravedad específica y la prueba de K en el suelo, aunque los coeficientes de correlación y las contribuciones a los modelos de regresión fueron relativamente bajos. Parece ser factible encontrar una fórmula general para los objetivos distinta a la de una mayor producción (por ejemplo potencial de lavado de nutrientes). La relación consistente de los componentes de la textura de suelo en nuestros modelos sugiere que la vigilancia del agua disponible en el suelo, un factor estrechamente vinculado a la textura del suelo, debería incluirse en cualquier trabajo futuro.

INTRODUCTION

Before certain tools and techniques associated with precision agriculture became available, several studies had been conducted to identify causes of within-field spatial variability.

TABLE 1—*Total precipitation and irrigation and other details of the fields.*

Year	Precipita-tion (mm)	Irriga-tion (mm)	Field	Area (ha)	Potato Variety	Harvest Days
1998	58.9	719	1	30	Shepody	Aug 20-21
1998	58.9	1063	2	40	Russet Burbank	Oct 12-14
1999	6.6	934	3	40	Russet Burbank	Sep 30-Oct 2
2000	40.9	663	4	30	Shepody	Jul 27-29

Topography has been reported to influence plant growth (Ruhe and Walker 1968), largely through aspects of soil water storage (Hanna et al. 1982; Sinai et al. 1981). Other soil properties such as thickness of A horizon, organic matter content, pH, nutrient concentrations (Kleiss 1970; Malo et al. 1974), and depth to free $CaCO_3$ (De la Rosa et al. 1981) have been reported to vary with landscape position which may partly explain within-field spatial variability in yield.

The relationship between yield of various crops and soil properties using a variety of techniques has been evaluated in several investigations with varying degrees of success. Studies where regression analyses were used to evaluate the relationship of crop yield to selected soil properties have found that these methods were useful for assessing variability in the relationship (Cambardella et al. 1996; Cox and Wardlaw 1999; Johnson et al. 1999; Khakural et al. 1996; Machado et al. 2000; Sudduth et al. 1996). Similar studies relating soil properties to yield are rare in potato (*Solanum tuberosum* L.). Using correlation analysis, Schneider et al. (1997) attempted to relate selected soil, weed, and topographic variables to potato yield and quality and observed few consistently strong relationships, perhaps due to their limited data set. The objective of this study was to test relationships between potato yield and quality and specific soil properties using correlation and regression analyses on a larger data set.

MATERIALS AND METHODS

Soil and plant data were collected from four selected center-pivot-irrigated, uniformly fertilized commercial potato fields in southeastern Washington (119.1 °W, 45.9 °N) from 1998 to 2000. Topography of the farm ranged from gently undulating to very steep with within-field elevation changes ranging from 5 to 50 m. The predominant soil is mapped as Hezel loamy fine sand (loamy, mixed, nonacidic, mesic Typic Torriorthent).

Different potato fields were used as sites each year (Table 1), which reflects the crop rotation typical of the Washington growing region area. For example, Field 1 was a study site only in 1998 because it was planted to corn (*Zea mays* L.) and wheat (*Triticum aestivum* L.) in 1999 and 2000, respectively. 'Russet Burbank' was grown in 1998 and 1999 and 'Shepody' was grown in 1998 and 2000 (Table 1). Due to the low rainfall typical of central Washington, all fields were irrigated (Table 1) to best meet plant water requirement. Also typical of this area of Washington, monthly temperatures varied considerably, with 1998 considered a hot year, whereas the temperatures in both 1999 and 2000 were less extreme. Thus, due to differences in annual climatic conditions and cultivars, each field was analyzed separately.

Soils were sampled at 0.4-ha square grid intervals each year prior to fertilizer application. The grid points were located using a Trimble AG GPS 122 (Trimble Navigation Systems, Sunnyvale, CA). Each soil sample was a composited sub-sample collected as ten 30-cm deep cores taken within a 1-m radius of each grid point. The soil samples were analyzed by a commercial laboratory. Soil nitrate (NO_3-N) and ammonium (NH_4-N) were determined colorimetrically on KCl extracts (Mulvaney 1996) (not measured on Field 1), soil phosphorus (P) was extracted with Na_2CO_3 and analyzed spectrophotometrically (Kuo 1996), soil potassium (K) was extracted with sodium acetate and determined by atomic absorption (Helmke and Sparks 1996), and soil organic matter (OM) was determined by dry combustion (Nelson and Sommers 1996). Soil pH was measured on a 2:1 water:soil mixture. Soil particle size distribution was analyzed over a 24-h period with readings at 0.5, 1, 3, 5, 10, 30 min and 1, 2, 5, and 24 h using a hydrometer (Gee and Bauder 1986).

All in-season fertilizer (~220 kg/ha N), pest control chemicals, and irrigation water application was made by the grower in uniform applications across the field. Irrigation was applied in 30- to 33-h sets to ensure that different parts of the field were irrigated at different times during the day throughout the season. Fertilizer application rates were based on field average nutrient levels and followed current Washington state guidelines (Lang et al. 1999). Four to five days before commercial potato harvest, at each original grid point, a 3-m row length, where plant stand was relatively uniform (no missing plants), was harvested using a one-row digger attached to a small field tractor. Tubers were then cleaned, weighed for point yield data, classified by weight, and each class weighed and sub-sampled for specific gravity determination (Dunn and Nylund 1945).

TABLE 2—*Mean and standard deviation (in parentheses) of the variables gathered from selected center-pivot irrigated potato fields at a commercial farm in southeastern Washington.*

Variable Name or Description	Field			
	1	2	3	4
ELEVATION (m)		286 (6)	281 (3)	252 (3)
From preplant soil samples				
NO3N (mg/kg)		3.36 (1.60)	3.12 (1.34)	8.19 (2.29)
NH4N (mg/kg)		15.80 (2.94)	17.60 (4.83)	6.09 (1.90)
P (mg/kg)	14.4 (8.9)	26.2 (7.7)	15.6 (4.5)	36.1 (7.2)
K (mg/kg)	225 (47)	176 (53)	168 (30)	233 (49)
CaCO3 (meq/g)	1.09 (0.70)			
OM (g/kg)	7.6 (1.9)	11.3 (3.8)	10.3 (1.9)	12.6 (1.3)
pH	6.85 (0.73)	6.19 (0.61)	6.85 (0.3)	5.48 (0.2)
CEC (meq/g)	10.81 (1.76)			
SAND (g/kg)	719 (105)	799 (79)	825 (72)	766 (70)
SILT (g/kg)	253 (98)	172 (70)	142 (63)	185 (64)
CLAY (g/kg)	28 (14)	29 (15)	32 (13)	49 (16)
From harvest samples				
Total Count per 3-m row	94 (12)	112 (18)	133 (23)	90 (17)
Specific Gravity	1.071 (0.005)	1.073 (0.004)	1.082 (0.004)	1.067 (0.003)
Class: 0-114 g (%)	24.0 (6.3)	53.8 (8.3)	37.1 (9.0)	36.6 (7.1)
Class: 11-170 g (%)	21.5 (4.8) 20.3 (4.2) 22.6 (4.0)	22.4 (5.4)		
Class: 170-284 g (%)	34.3 (6.1) 18.1 (5.1) 25.0 (5.6)	26.3 (5.3)		
Class: > 284 g (%)	20.1 (7.0)	7.9 (4.0) 14.8 (6.0)	14.9 (5.6)	
No. of point yield samples	81	99	89	77
Total no. of grid points	82	114	99	81

Statistical analyses were conducted on the data set of each of the four fields. The data sets from the four fields were not combined because of varietal, edaphic, and year-to-year climatic differences. Normal distribution test using the Kolomogorov-Smirnov method (Yates and Yates 1989) was conducted for each variable in a data set. Using the GS+ geostatistics program (Gamma Design Software 1998), block-kriging was performed on the data sets which were normally distributed while lognormal block-kriging was conducted on data sets that were lognormally distributed. Block size was 63.6 x 63.6 m and discretizing grid was 3 x 3. Table 2 shows variables measured from preplant soil and harvest samples.

The CORR and STEPWISE procedures of SAS (SAS Institute 1999) were used for correlation and stepwise multiple linear regression analyses to estimate relationships between dependent and independent variables. In the regression analysis, the dependent variables were point yield, total tuber count, and specific gravity. The independent variables were elevation and soil properties listed in Table 2. Only raw or point data sets were used in correlation analysis. Both data sets (raw data from grid points and corresponding block-kriged data) were used in regression analysis.

RESULTS AND DISCUSSION

Correlation Analysis

Relationships between yield and quality factors and measured soil properties varied between the four fields. For example, yield and the yield component total tuber count were unrelated to soil properties in Field 4 and specific gravity was unrelated to soil properties in Field 2 (Table 3).

However, stronger relationships were found between soil physical properties and yield variables (Table 3). Point yield was positively correlated to sand in Field 1 and to clay in Field 2. It was also negatively correlated to silt and OM in Field 1. In both of these fields, total tuber count was correlated with the same factors as yield and was also negatively correlated with K in Field 1 and pH and sand in Field 2. Point yield and total tuber count in Field 1 were positively correlated with sand and in Field 2 were positively correlated with clay, results which may appear to be contradictory. However, there was a positive correlation between the proportion of tubers in the largest size classification (>284 g) and elevation (correlation coefficient = 0.27, P = 0.01) in Field 2. The proportions of sand and clay in each of these fields may have been related to internal water-holding capacity or drainage in these fields.

Nitrogen (N) played a role in potato yield and yield components in Field 3. Both point yield and total tuber count were negatively correlated with NO_3-N. Point yield was also negatively correlated with soil pH whereas total tuber count was positively correlated with NH_4-N. Potato size distribution in Field 3 was related to NH_4-N such that small and large potato sizes were positively and negatively correlated with NH_4-N, respectively (correlation coefficients of 0.27, 0.21, -0.33, - 0.27 for 0-114g, 114-170g, 170 -284g, > 284g sized tubers, respectively, P < 0.05). The positive correlations between NH_4-N and total tuber count and between NH_4-N and the proportion of small potatoes (class: 0-114 g), and the negative correlation between NO_3-N and point

TABLE 3—*Pearson correlation coefficients between potato yield and soil variables for four center-pivot-irrigated fields at a commercial farm in southeastern Washington.*

Yield Variable	ELEVATION	Variable Measured From Preplant Soil Sample								
		NO3N	NH4N	P	K	OM	pH	SAND	SILT	CLAY
Field 1 (n = 81)										
Point Yield				ns	-0.22*	-0.25*	ns	0.33***	-0.33***	ns
Specific gravity				-0.38***	-0.29**	-0.38***	ns	ns	ns	ns
Total count				ns	-0.27**	-0.24*	ns	0.24*	-0.24*	ns
Class: 0-114 g				ns	ns	ns	ns	ns	ns	ns
Class:114-170 g				ns	ns	ns	ns	ns	ns	ns
Class:170-284 g				ns	ns	-0.26*	ns	ns	ns	ns
Class: > 284 g				ns	ns	ns	ns	ns	ns	ns
Field 2 (n = 99)										
Point Yield	ns	ns	ns	ns	ns	ns	ns	ns	ns	0.20*
Specific gravity	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Total count	ns	ns	ns	ns	ns	ns	-0.26**	-0.20*	ns	0.24*
Class: 0-114 g	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Class: 114-170 g	ns	0.22*	ns	ns	ns	ns	ns	ns	ns	ns
Class: 170-284 g	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Class: > 284 g	0.27**	ns	ns	ns	ns	ns	ns	ns	ns	
Field 3 (n = 89)										
Point Yield	ns	-0.21*	ns	ns	ns	ns	-0.22*	ns	ns	ns
Specific gravity	ns	ns	ns	-0.28**	-0.41***	0.26**	0.41***	0.39**	-0.39**	ns
Total count	ns	-0.23*	0.21*	ns	ns	ns	ns	ns	ns	ns
Class: 0-114 g	ns	ns	0.27*	0.27*	ns	ns	ns	ns	ns	ns
Class:114-170 g	ns	ns	0.21*	ns	ns	-0.23*	ns	ns	ns	ns
Class:170-284 g	ns	ns	-0.33**	-0.35***	ns	ns	ns	ns	ns	ns
Class: >284 g	0.22*	ns	-0.27**	ns	ns	ns	ns	ns	ns	ns
Field 4 (n = 77)										
Point Yield	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Specific gravity	ns	ns	ns	-0.24*	-0.27*	-0.25*	ns	ns	ns	ns
Total count	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Class: 0-114 g	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Class: 114-170 g	ns	ns	-0.27*	ns	ns	ns	ns	ns	ns	ns
Class: 170-284 g	ns	ns	ns	ns	ns	0.27*	ns	ns	ns	ns
Class: > 284 g	ns	-0.28*	ns	ns	ns	ns	ns	ns	ns	ns

*, **, *** Significant at the 0.05, 0.01, and 0.001 probability levels, respectively; ns = not significant.

yield suggest that this field may have been supplied with more N than was optimal for potato production.

Significant negative correlations between specific gravity and P and K were found in Fields 1, 3, and 4. There was also a relationship between OM and specific gravity in these fields. However, the correlation was negative in Fields 1 and 4 and positive for Field 3.

Overall, soil variables that correlated with yield and quality varied between fields, a result that is consistent with reports on other crops (Khakural et al. 1996; Redulla et al. 1996). The consistent relationships with soil physical properties suggest that an unmeasured soil property, such as drainage or water-holding capacity, may have a strong influence on yield and quality. Rela-

tionships between yield and yield components and N in Field 3 suggest that a general prescription formula for variable rate nutrient management for potato yield and yield components may be limited by site- and possibly season-specific differences. Yet, the consistent negative relationships between P and K and the quality specific gravity suggest that variable rate nutrient management for quality may be beneficial.

Stepwise Regression Analysis

Less than half (30%-41%) of the variability in point yield was accounted for by factors measured in this study. Consistent with the outcomes of correlation analysis, models relating point yield to pH, soil separates (i.e., sand, silt, or clay) and K had the high-

est partial R^2. Negative relationships with sand and positive relationships with clay were found in three of the four fields. The range of variability related to total tuber count was even greater (10%- 65%). For this variable, the highest R^2 found was 0.65 for block-kriged data in Field 2 with clay contributing the largest partial R^2 (0.52, $P < 0.0001$). The average clay content for the field was typical of the area (2.9%), with a range from 0.4% to 6.9%, indicating that a small difference in this variable can have a large effect on tuber number (total count). The second highest R^2 was in Field 3, with elevation contributing 0.19 to the total of 0.40 (Table 4). Therefore, clay and elevation appeared to explain the greatest proportion of variability in yield and tuber count. It is likely that this effect is related to water movement and availability.

TABLE 4—*Results of stepwise linear regression analysis on data from four fields with uniform rate fertilizer treatment. Independent variables were the altitude and those parameters measured from the preplant soil samples.*

Dependent Variable	Kind of Data	n	R^2	Variables in Equation[1]
			Field 1	
Point Yield	Point	81	0.18	SAND, (K)
	Block-kriged	317	0.39	(pH), SAND, CEC, (P)
Total Count	Point	81	0.18	(K), SAND, (CaCO3)
	Block-kriged	317	0.10	(CaCO3), (P), SAND
Specific Gravity	Point	81	0.23	(P), (OM)
	Block-kriged	317	0.64	(pH), (K), (P), SAND, CaCO3, CLAY
			Field 2	
Point Yield	Point	99	0.09	CLAY, ELEVATION, OM
	Block-kriged	317	0.41	Clay, OM, (SAND)
Total Count	Point	99	0.12	(pH), CLAY, (P)
	Block-kriged	317	0.65	Clay, NO3N, (pH), P, (NH4N), OM
Specific Gravity	Point	99	none	
	Block-kriged	317	0.16	(K), ELEVATION, CLAY, NO3N, (pH), P, (SAND)
			Field 3	
Point Yield	Point	48	0.30	(pH), OM, (NO3N)
	Block-kriged	317	0.32	(NH4N), (K), CLAY, NO3N, (pH), P, (SAND), OM
Total Count	Point	48	0.29	(ELEVATION), P
	Block-kriged	317	0.40	(ELEVATION), NH4N, (OM), P, (pH)
Specific Gravity	Point	48	0.45	SAND, (NO3N), ELEVATION, (P)
	Block-kriged	317	0.47	(K), ELEVATION, pH, NH4N, P
			Field 4	
Point Yield	Point	74	0.06	(pH), (P)
	Block-kriged	317	0.34	(pH), P, (SAND), NH4N, Clay
Total Count	Point	74	0.06	CLAY, NO3N
	Block-kriged	317	0.32	NO3N, (pH), (CLAY), (SAND), (K)
Specific Gravity	Point	74	0.11	(K), (ELEVATION)
	Block-kriged	317	0.42	(K), (P), (pH), (CLAY), (SAND), (OM)

[1]Significance level was 0.15 for variables to enter into the equation; the variables are arranged in order of decreasing partial R^2; a variable in parentheses had a negative coefficient in the equation.

Relationships between soil chemical properties and yield variables were found. However, no single nutrient appeared in the models for all fields and only K appeared in Field 1 for both point and block-kriged data. In these commercial fields, the macronutrients N, P, and K were amply applied, and it is unlikely that they limited plant growth. In fact, K may have been present in excess, since when there was a significant correlation between point yield or tuber count and K, it was negative (Table 3). This supports recent findings that Washington State University's current guidelines for soil test K may have consistently prescribed a higher amount of K than may be required (Davenport and Bentley 2001).

Point yield was negatively correlated with soil pH in every field except Field 1. The highest partial R^2 was with this variable in block-kriged data from Fields 2 and 4 and point data in Field 3. It is unlikely that this is a pH effect alone. The negative correlation with pH may be an indicator of variability in availability of a nutrient like P, which is highly pH dependent. The positive correlation between point yield and P in Fields 3 and 4 support this.

As found in correlation analysis, the variable K was found to be negatively related to specific gravity in three of the four fields and had the highest partial R^2 in two fields. This is consistent with findings from small plot research indicating that high K rates are associated with reduced specific gravity (Westermann et al. 1994) and implies that this relationship can be translated across whole fields. Either soil separates or elevation appeared in the regression models for all fields. These factors suggest a drainage component.

In this study, soil texture had the most significant impact on yield. Regression analysis of yield with block-kriged data showed a negative relationship with sand and positive with clay in all fields except Field 1. However, this is most likely that this rela-

tionship is indirect. Soil texture is related to soil water-holding capacity and, hence, to soil water availability (Hanna et al. 1982). The dominant factors contributing to variability in point yield appear to be variables related to soil water availability (e.g., soil separates). This observation is supported by findings from a four-year study on two potato cultivars in Canada where uneven application of irrigation water influenced potato tuber size and number (McKenzie et al. 2000). Although these fields were irrigated, within-field variability in soil physical properties (e.g., texture) or unmeasured factors, such as wind effects on irrigation uniformity, at critical times during crop growth may have generated within-field variability in available soil water.

The R^2 values reported here were generally low compared to reports on other crops (Cambardella et al. 1996; Sudduth et al. 1996), but similar to others (Karlen et al. 1999; Machado et al. 2000). Unmeasured variables may have affected the spatial yield variability recorded here. These variables may include soil physical characteristics affecting water availability to the plant, e.g., soil depth (De la Rosa et al. 1981). Further, pest pressures from weeds, insects, and diseases, not measured in this study, may be an important group of site-specific variables (Fleischer et al. 1997; Johnson et al. 1997).

CONCLUSIONS

A general prescription formula for variable nutrient management for potato yield and quality may be limited in its use because yield-driving factors varied from field to field and possibly from season to season. With stepwise linear regression the most frequent, and often the strongest, relationship between yield and soil chemical properties was with soil pH, a relationship which was found in both varieties and all years. This is most likely an indirect effect of pH since nutrient availability is influenced by soil pH (Brady and Weil 1999). The relationship with soil pH indicates that this is a measurement that may be useful for developing variable rate nutrient strategies.

There strongest relationship found with a plant nutrient was the negative relationship between K and specific gravity. The relationship has much support in small plot research and the results of this study indicate that it holds across whole field scale. Thus, this may be an element to target for developing variable rate fertilizer prescriptions in potato.

There were some indications of relationships between yield and quality and nitrogen but the inconsistency from field to field of negative and positive relationships make these difficult to interpret. However, factors other than yield (e.g., potential nutri-

ent leaching) may be important considerations and prescriptions for this purpose may show more promise with a nutrient like N (Whitley et al. 2000).

The results of this research suggest that sampling for the relatively static variable of soil texture may be of value. The results also suggest that any further work in this area should include *in situ* monitoring of soil water availability as many of the factors associated with potato yield and quality are implicitly related with soil water availability.

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